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HIGH TIME RESOLUTION MEASUREMENTS OF EARTH ROTATION

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ABSTRACT

High time resolution measurements of Earth rotation and atmospheric angular momentum (AAM) and their interpretation have been proposed as a major research thrust for the 1990s. An extensive campaign, SEARCH'92, is now under way to obtain these measurements utilizing all space geodetic techniques and to collect the best available complementary geophysical, oceanographic and atmospheric data. This paper discusses its motivation and scientific benefits and reviews international cooperation in several measurement campaigns with particular emphasis on SEARCH'92. Recent analysis results are highlighted.

1. INTRODUCTION

High time resolution measurements of Earth rotation and atmospheric angular momentum (AAM) and their interpretation have been proposed as major research areas for the 1990s, both by the workshop held at Erice in 1988 on the "Interdisciplinary Role of Space Geodesy" and by the NASA Workshop on Geodynamics and Geology held in July 1989, to plan NASA Solid Earth Science Programs for the coming decade. The importance of the determination of rapid Earth rotation and its implication for geodynamics was recognized by the International Union of Geodesy and Geophysics (IUGG) in Vienna (August 1991) through a union resolution; as a result, a major campaign, SEARCH'92 (Study of Earth-Atmosphere Rapid CHanges), for high time resolution (sub-daily) measurements of Earth rotation by all of the space geodetic techniques, is being coordinated by the International Earth Rotation Service (IERS) and is being held in conjunction with the IGS Campaign (June 21–September 22, 1992). A special intensive period (Epoch'92) extended from July 25 through August 8, 1992.

This paper highlights progress and planning for high time resolution measurements of Earth rotation. The second section discusses the motivation and scientific benefits from these measurements, while the third section reviews international cooperation in several measurement campaigns with particular emphasis on the current SEARCH'92 campaign. Section 4 highlights recent advances in analysis and interpretation, while the final section presents a summary.

A recent paper, Dickey /1/ reviews atmospheric excitation of the Earth's rotation and provides a more detailed account of recent developments. The reader is referred to several more detailed accounts of the excitation of Earth orientation changes; references to early work can be found in the classical monograph on the subject by Munk *et al.* /2/ and to more recent work in various monographs and other publications /3/.

2. MOTIVATION AND SCIENTIFIC BENEFITS

The scientific benefits to be obtained from these campaigns include increased understanding of the properties and origin of short-period fluctuations in the Earth's orientation, improvements to the tidal models at sub-monthly periods, and improved ability to predict changes in the Earth's rotation up to a month in advance. A major goal is to observe and understand the interactions of the atmosphere and ocean with the rotational dynamics of the Earth, and their contributions to the excitation of Earth rotation variations over time scales of hours to months (see Fig. 1). At these frequencies, a number of geophysical processes are thought to be capable of affecting the Earth's rotation, including atmospheric wind and pressure changes, oceanic current and sea level changes, oceanic and solid Earth tidal motions, and seismic motions. High-frequency measurements, and complementary analyses, can be expected to lead to delineation of short-period tidal, atmospheric, oceanic, and seismic effects on length-of-day (LOD) and polar motion. These in turn will improve our understanding of

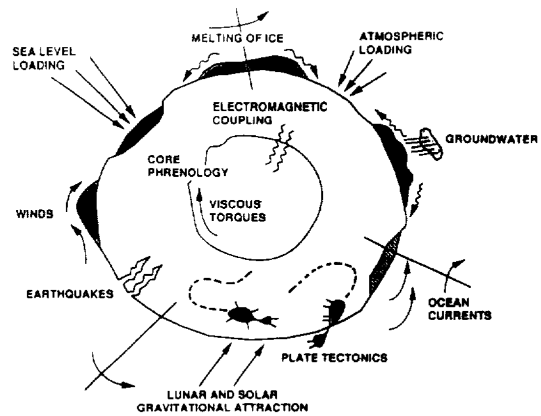


Fig. 1. Schematic illustration of the forces that perturb Earth rotation. After /21/.

broad-band wobble excitation processes, fluid-core resonance characteristics, and mechanisms of oceanic/atmospheric coupling to the solid Earth.

In particular, the Earth's angular momentum budget (both axial and non-axial) can be examined at high frequencies. The elucidation of the relation between LOD and AAM at high frequencies is central to our understanding of the Earth's angular momentum budget and is currently an area of active research /4-6/. Fig. 2 illustrates the striking similarities between these two series. Significant coherence is found between the LOD and AAM at periods down to 8 days, with lack of coherence at shorter periods caused by the declining signal-to-measurement noise ratios of both data types /6/. Higher accuracy and more frequent data are needed to resolve the exchange of angular momentum between the Earth and the atmosphere at shorter periods. Although no significant lags or leads at the few day level have been established (indicating little or no non-tidal oceanic contribution), the oceans, via barotropic waves, could contribute on short time scales (a few days or less) to the Earth's angular momentum budget /7/. Hence, a comparison of AAM and LOD at these high frequencies could uncover the ocean's role and further elucidate our understanding of the dynamic interaction between the solid Earth and the atmosphere, allowing the role of the atmosphere and oceans in Earth orientation variations at high frequencies to be quantified. The

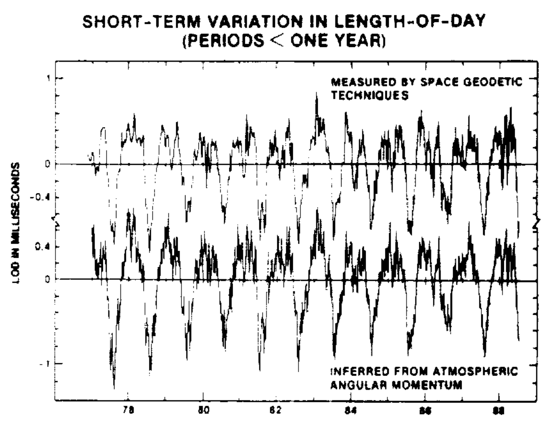


Fig. 2. Time series of the sum of the seasonal and intraseasonal LOD components, with the upper curve measured by space geodetic techniques and the lower curve inferred from routine daily determinations of changes in the axial component of the atmospheric angular momentum made by the U. S. National Meteorological Center. Periods greater than one year in both series have been filtered out.

appropriateness of the inverted barometer approximation for the ocean's response to atmospheric pressure forcing at high frequencies could be investigated, and the respective roles of the mountains and wind stress torque in transferring angular momentum between the solid Earth and atmosphere examined.

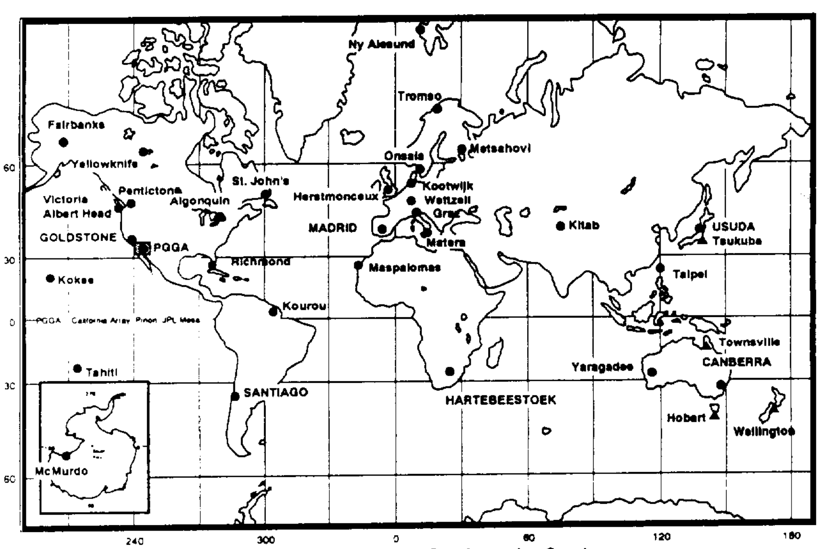
3. MEASUREMENT CAMPAIGNS

Thus far, three major campaigns have been coordinated, allowing high temporal resolution measurements of Earth rotation over extended time periods. The NASA Crustal Dynamics Project VLBI (Very Long Baseline Interferometry) Group at Goddard Space Flight Center conducted the first Extended Research and Development Experiment (ERDE) in October, 1989, designed to obtain high time resolution measurements of the Earth's orientation by the VLBI technique and to test improvements in the VLBI measurement system /8/; these special sessions resulted in nearly continuous sub-hourly measurements over the 17-day period and served as a prototype for future efforts.

The GIG'91 Measurement Campaign (GPS IERS and Geodynamical Experiment), coordinated by the International Earth Rotation Service, was held between January 22 and February 13, 1991 with one of its prime objectives being the evaluation of the ability of GPS to recover Earth rotation parameters. The analysis of these data provided high quality daily measurements of polar motion /9-10/ as well as sub-daily measurements of Earth rotation variations /11/.

The on-going SEARCH campaign involves all space geodetic techniques with the best available complementary geophysical, atmospheric and oceanographic data being collected. Coordination is being effected by the International Earth Rotation Service (IERS). A joint International Association of Geodesy/International Astronomical Union (IAG/IAU) Special Study Group, Rapid Earth Orientation Variations, has been formed to (1) interface with the IERS in the determination of rapid variations in Earth rotation by the space geodetic techniques; (2) advocate for the best possible auxiliary data from geophysical, atmospheric and oceanographic sources; (3) encourage improvements in measurement techniques (including geodetic, atmospheric, oceanographic and geophysical); and (4) encourage cooperative multidisciplinary studies.

During the SEARCH and EPOCH'92 campaigns, geodetic Earth rotation and polar motion measurements are expected from the GPS, VLBI, SLR and LLR techniques; complementary geophysical data sets are also being archived.



International GPS and Geodynamics Service Operational Network as of August 1992

Fig. 3a. GPS Observing Network

Global Positioning System (GPS)

Recognizing the increasing use of the Global Positioning System (GPS) for geodesy and geophysics and that this system will play a major role in global and regional studies of the Earth, the IUGG in Vienna (August, 1991) recommended through a union resolution that the development of an International GPS Geodynamic Service (IGS) be explored. At its May 1, 1992 meeting the Directing Board of IERS officially adopted GPS as a contributing technique for the terrestrial reference frame and Earth rotation determination. As a test of the IGS concept, the IGS Oversight Committee organized a campaign for the period June 21–September 22, 1992 with a special intensive period (EPOCH'92) extending from July 25 through August 8, 1992. GPS results are expected throughout the entire three month campaign.

The observing GPS network is displayed in Fig. 3a; it consists of an operational core network of about 30 receivers with up to an additional 80 GPS stations participating during the EPOCH'92 period. Standard GPS ephemerides and polar motion are being generated by 6 analysis centers (Table 1) within 2 weeks of receipt of data. The analysis of these data are discussed in the next section.

Satellite Laser Ranging

A world-wide network of ~30 stations (Fig. 3b) is supporting tracking to LAGEOS and ETALON satellites. Currently, 3-day average polar motion is being produced operationally with an accuracy of 0.3–0.4 mas (~ 1 cm). With further analyses, pole position results with an accuracy at the ~0.5 mas level are expected, with resolution of some components at the sub-daily level.

Lunar Laser Ranging (LLR)

The LLR technique plans to contribute to the campaign by optimizing its ranging strategy for Earth rotation during this period. It is hoped that CERGA, a dedicated lunar station, will be able to support sub-daily determinations.

VLBI

The VLBI measurement program consists both of routine operational programs (e.g., IRIS-A, NAVNET) as well as an intensive observing plan during Epoch'92; the global VLBI Network for SEARCH is given in Fig. 3c. Collectively, IRIS-A and NAVNET will operationally provide 3-component Earth rotation (UT1) and polar motion measurements on a twice-a-week basis with 24-hour observing programs; daily intensive UT1 measurements will be made utilizing the Westford and

TABLE 1 GPS Data Processing Centers

• CODE
Center for Orbit Determination — Europe
Astronomical Institute of the University of Berne (AIUB), Switzerland
• ESA/ESOC
European Space Agency/European Space Operations Center
Darmstadt, Germany
• GFZ
Geoforschungszentrum
Potsdam, Germany
• JPL
Jet Propulsion Laboratory/Caltech
Pasadena, California USA
• SIO
Scripps Oceanographic Institute/UCSD
La Jolla, California USA
• UTX/CSR
University of Texas at Austin, Center for Space Research
Austin, Texas USA

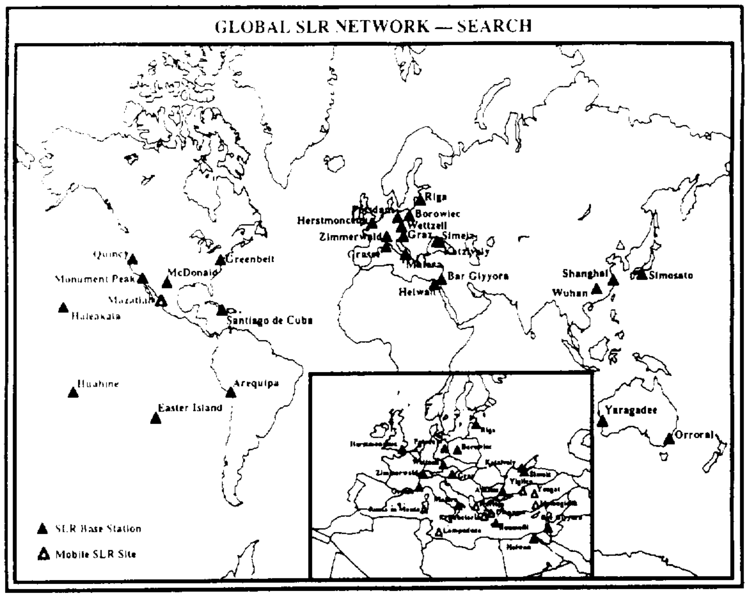


Fig. 3b. SLR Observing Network

Wettzell stations. There was essentially continuous coverage on two simultaneous VLBI networks during the period July 27-August 10, which will be useful in error analysis. During this time, coverage was provided by the NASA-sponsored Extended R&D sessions, the scheduled POLARIS/IRIS and the augmented USNO NAVNET/NAVEX programs. The R&D experiments utilized the strongest network possible and the most optimized observing schedules.

The accuracies expected for VLBI determinations of Earth orientation parameters (EOP) during the EPOCH-92 campaign are functions of several factors including network geometry, observation rate, and the observing mode (which determines the precision of individual observations). Estimated EOP accuracies are given in Table 2 for ~one-day intervals /12/. EOP accuracies at higher time resolutions should scale roughly with the inverse of the square root of the time interval. Thus, over 3-hour time intervals the EXT-R&D and NAVEX sessions are expected to yield results comparable in accuracy to the one-day averages obtained from the operational networks (IRIS-A and NAVNET). Under the assumption of perfect site and source positions, more optimal predictions of VLBI performance can be obtained. For example, MacMillan and Ma /13/ estimated, for a 24-hour period, one-sigma uncertainties of 3, 6, 9 μsec for the ERDE, IRIS and NAVNET networks respectively.

At this time, the operational VLBI data are available. However, the special intensive observations require special analysis and will be available at a later date. Indications are that the specially planned VLBI experiments were "95+%" successful.

TABLE 2 Estimates of the EOP Accuracies Obtained from the Various Observing Series for ~One-Day Intervals

SERIES	X,YSIGMAS (microarcsec)	UT1SIGMA (microsec)
IRIS-A	350-400	15-20
NAVNET	350-400	15-20
EXT-R&D	~100	<10
NAVEX	~100	<10
Intensives	---	100

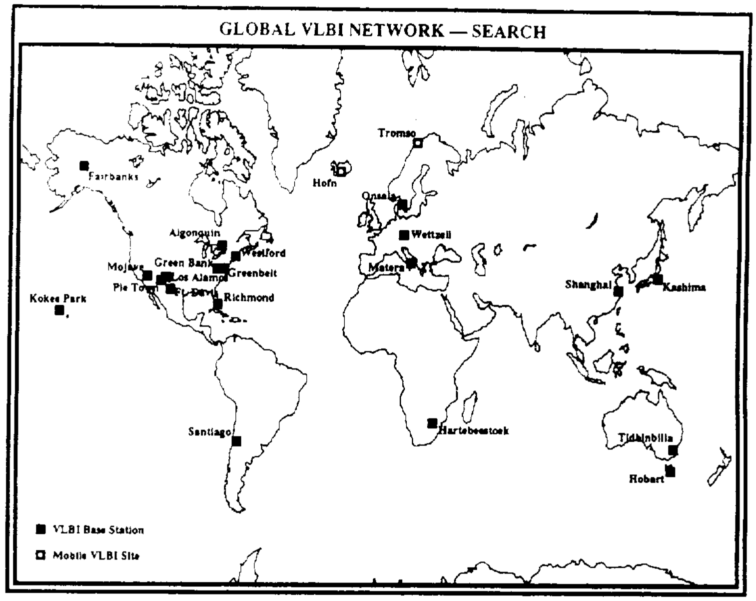


Fig. 3c. VLBI Observing Network

Complementary Geophysical Data

The primary complementary geophysical data sets to be acquired are series of atmospheric angular momentum and Earth-atmosphere torques. There are four meteorological data centers contributing standard AAM products to the IERS Sub-Bureau for Atmospheric Angular Momentum (see Table 3). The ECMWF, NMC and UKMO data are available now in near real time, while JMA data are typically sent in 3-month intervals upon request. AAM data are typically archived twice daily. As part of this special campaign, 6-hourly AAM measurements are now available from the NMC and ECMWF analyses. The other standard data types are outlined in Table 4. The meteorological centers maintained their standard operations during this period. Calculations of Earth-atmosphere torques are now under way at the NMC and can be supplied to the geodetic community for these campaigns. These torques involve the dynamic transfer of momentum between Earth and atmosphere by means of pressure differences across mountains and also by friction at the Earth's surface.

TABLE 3 Availability of Atmospheric Angular Momentum (AAM) Estimates

	Starting Date of Series	
	Analysis	Forecast
• European Centre for Medium-Range Weather Forecasts (ECMWF)	1979*	April 1987
• Japan Meteorological Agency (JMA)	1983**	
• National Meteorological Center (NMC — USA)	1976*	November 1985
• United Kingdom Meteorological Office (UKMO)	1983*	December 1986

*Available in "real time"
**Data prepared by National Astronomical Observatory of Japan

TABLE 4 Atmosphere Data Sets Archived at IERS Sub-Bureau for Atmospheric Angular Momentum

Analysis Parameters	Specification
AAM Equatorial χ_1, χ_2 AAM Axial χ_3	Hemispheric values for wind, pressure & pressure + inverted barometer (ib)
Zonal Mean Zonal Winds [u] Zonal Mean Termperatures [T]	5°latitude intervals, 12 mandatory pressure levels
Mean Surface Pressure	Global average
Surface Pressure Coefficients	Triangular truncation to wave 4 zonals only to wave 20
Forecast Parameters	**Specification**
AAM Equatorial χ_1, χ_2 AAM Axial χ_3	Global forecast values at 12-h intervals to 10 days for wind, pressure, pressure + ib

4. HIGHLIGHTS OF ANALYSIS RESULTS

ERDE and GIG'91

The ERDE Campaign (see previous section) provided nearly continuous sub-hourly VLBI determinations over a 17-day period (see Fig. 4) during October 1989, while GPS measurements from the GIG'91 (held from January 22 through February 13, 1991) have been analyzed to produce high-quality daily measurements of polar motion (/9-10/ — see Fig. 5), as well as sub-daily measurements of Earth rotation variations (/11/ — see Figs. 6 and 7). Intercomparison of GPS-determined UT1R and polar motion variations with those determined from independent techniques (VLBI and SLR) indicates that GPS estimates are accurate to about ~2 cm (0.04 msec) (/11/ — see Fig. 6) for UT1 and to ~1 cm (0.4 mas) for polar motion /10/ — see Fig. 5, which is consistent with the quoted uncertainties.

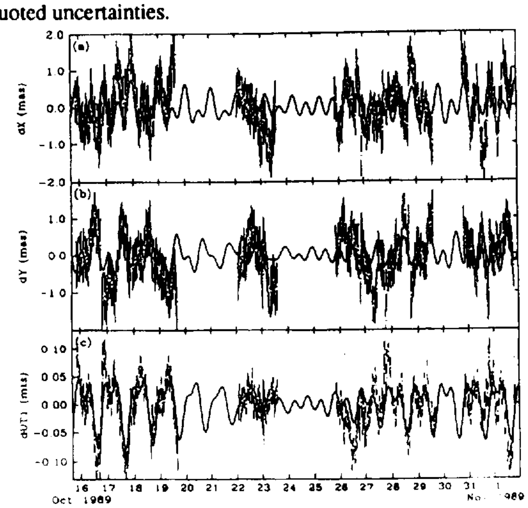


Fig. 4. Earth orientation series obtained during the ERDE VLBI campaign, filtered to emphasize the high-frequency component. The data are VLBI data results, while dotted lines indicate results from an empirically derived oceanic tidal model /5/.

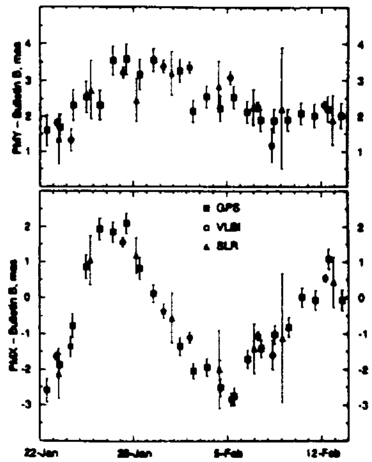


Fig. 5. Estimates of pole position with GPS, VLBI, and SLR. The polar motion series from these space geodetic techniques agree within their formal errors (~0.4 mas). After /10/.

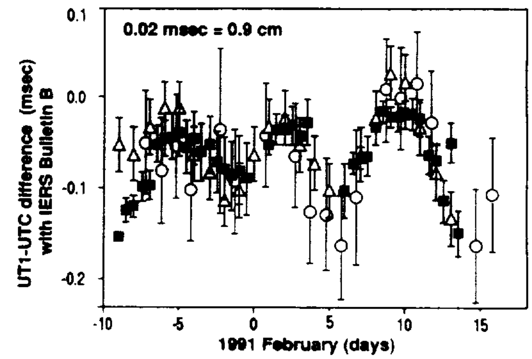


Fig. 6. Comparison of GPS UT1 estimates every 12 hours (time series is reset on February 1 and February 6) with daily VLBI estimates. This filled square indicates GPS results, while the open circle and triangle represent IRIS Intensive and Kalman Earth orientation filter values, agree respectively. After /11/.

Diurnal and semi-diurnal rotational variations were postulated by Yoder *et al.* /14/, who proposed that such signatures should arise from the interactions of the ocean tides with the solid Earth. Estimates of these variations were made by Baader *et al.* /15/ for the M_2 tide and were refined by Brosche *et al.* /16/ for the major diurnal and semi-diurnal tides. Herring and Dong /5/ used the approach of empirically fitting the major tidal components to sub-daily VLBI observations. Dickman /17/ developed the "broad-band" Liouville equation approach and determined the effects of the dynamic ocean tides on Earth rotation. Comparisons with the independent techniques of VLBI and GPS confirm the reality of a strong diurnal and semi-diurnal signature [~0.1 msec (5 cm) in amplitude — see Fig. 7 /11/]. The geodetically-determined UT1R variations place constraints on oceanic tidal models — see Fig. 8 /18/; results indicate excellent agreement with the models of Brosche *et al.* /16/ and Herring and Dong /5/. Predicted diurnal variations from the Dickman /17/ model show significant correlation with the observational results, but are too small in amplitude.

Daily polar motion values determined from observations acquired during the GIG'91 measurement campaign permit an unprecedented high time resolution investigation of the effect of the atmosphere on rapid polar motion variations — see Fig. 9 /19/. The wind and pressure terms are found to be of comparable importance in exciting the observed polar motions during this period with somewhat better agreement seen with the application of the inverted barometer approximation. Correlations as high as 0.88 are obtained between the observed polar motion and the AAM-induced series, with AAM variations explaining as much as 74% of the variance of the observed polar motion (Fig. 9). Thus, the atmosphere appears to be the dominant polar motion excitation source during the GIG campaign /19/.

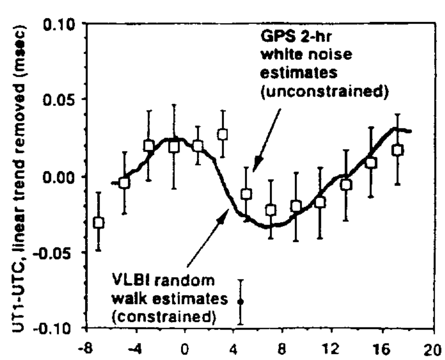
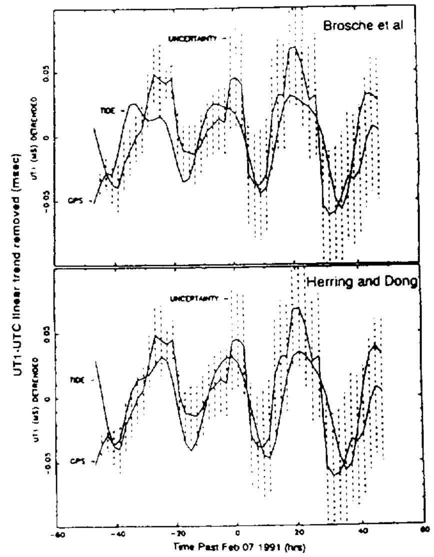


Fig. 7. Comparison of GPS and VLBI sub-daily estimates for UT1 variations. After /11/.



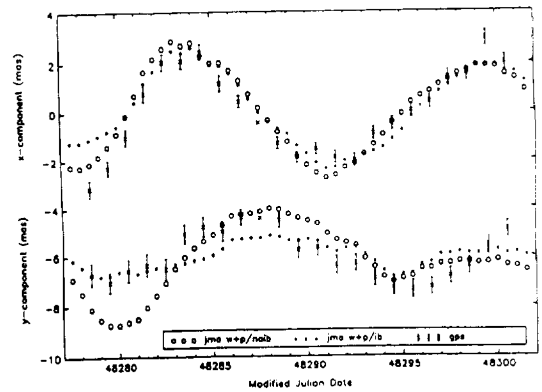


Fig. 8. Sub-daily UT1 Variations: (a) Comparison between GPS determinations and predictions from the Brosche *et al.* /16/ oceanic tidal model; (b) comparison between GPS determinations and predictions from the Herring and Dong empirical tidal model /5/, derived from a fit to VLBI data. In both figures, the dashed lines indicate the uncertainty associated with the GPS determinations, after /18/.

Fig. 9. The x-component (top) and y-component (bottom) of the observed and Japanese Meteorological Agency (JMA) AAM-induced polar motion series (both series have been high-pass-filtered using a cutoff period of 23 days). The crosses with error bars represent the observed series (one data point is plotted without error bars indicating that it is the interpolated point). The open circles represent the polar motion series induced by the JMA AAM χ-functions formed by summing the wind term with the pressure term computed under the rigid ocean approximation. The filled circles represent the polar motion series induced by the JMA AAM χ-functions formed by summing the wind term with the pressure term computed under the inverted barometer approximation, after /20/.

SEARCH Campaign

Since we are in the midst of the SEARCH Campaign, an evaluation of GPS results given here is limited to the operational polar motion results only. The determination of Earth rotation (UT1-UTC) from GPS is now under development at several centers and no doubt will be reported later in more detailed analyses.

Here, the JPL Kalman Earth Orientation Filtered (KEOF — see Fig. 10) is utilized as the standard series for comparison; this series optimally combines determinations from SLR and VLBI determinations to form a high-quality series in which the issues of reference frames and the unevenness of data quality and quantity have been addressed /20/. The effects of the various input data are seen in Fig. 10. Fig. 11 compares the GPS determined x- and y-components of polar motion between themselves and the referenced KEOF series. Common structures are seen in both series; for example, a dip is observed in all series near July 15 in the x-component and a long-term rise is seen in y after this day.

Table 5 lists the weighted rms scatter of the six GPS series against the KEOF reference as well as the scatter between the input VLBI/SLR data and the resultant KEOF series. It should be stressed that there are no GPS data included in the filter. There is considerable range in rms scatter, from 0.4 to 2.8 mas; this effect is also evident in Fig. 11. Three centers are producing series with 1.0 mas or smaller scatter: CODE, JPL and SIO. The analysis systems are evolving and being improved. For example, JPL changed its fiducial and reference frame strategy in late July, resulting in reduced errors and a decreased rms scatter (0.36 mas in x and 0.56 mas in y). It is interesting to note that this is comparable to the scatter of input data that are actually used. These initial results are indeed encouraging and confirm the ability of GPS to do high-quality polar motion determinations.

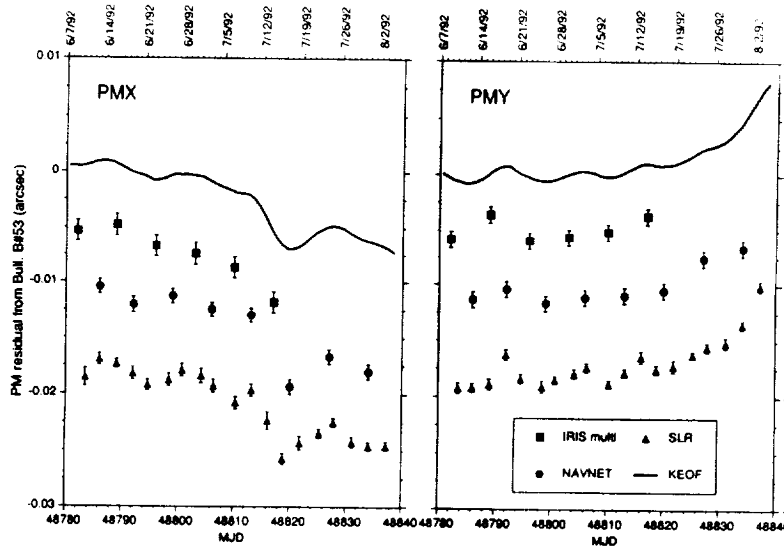


Fig. 10. Polar motion (x and y) obtained with the JPL Kalman Earth Orientation Filter (KEOF) displayed with the input data sets. Offsets have been added arbitrarily for clarity of presentation /22/.

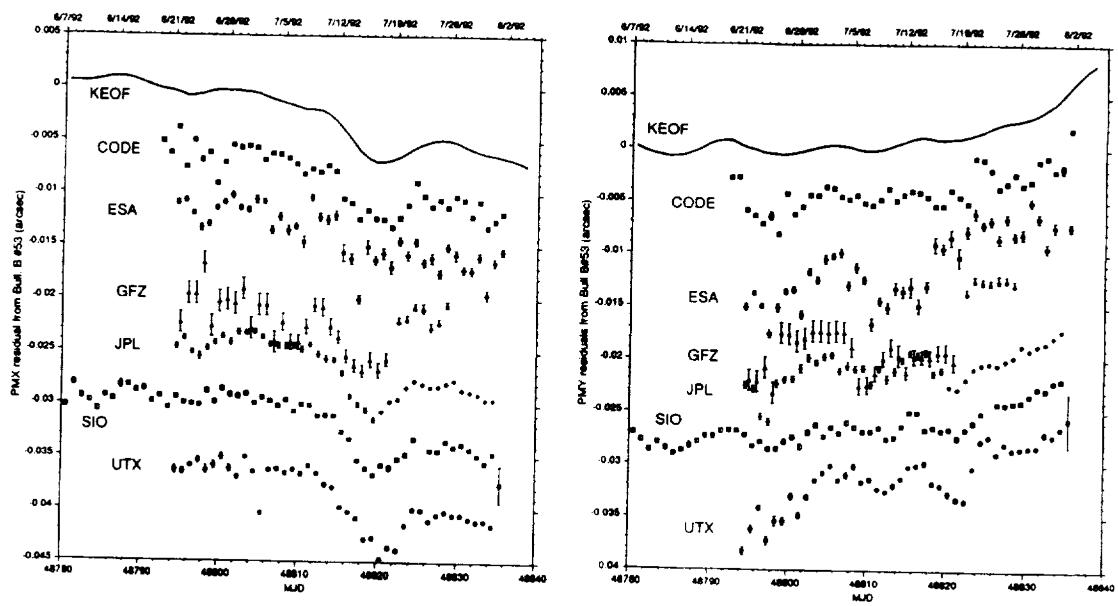


Fig. 11. Comparison of KEOF polar motion (x-component shown in 11a and y-component in 11b) with that determined from the various operational GPS centers — see Table 1. Note that the GPS data are not an input data set for the filtered series.

TABLE 5 Weighted RMS of GPS with respect to KEOF (after removing weighted mean difference)

GPS Series	PMX(mas)	PMY (mas)
CODE	0.82	1.01
ESA	1.26	2.38
GFZ	2.29	2.82
JPL	0.47	0.85
SIO	0.68	0.63
UTX	1.07	1.33
JPL (92 P 02)	0.36	0.56

Weighted RMS of VLBI/SLR with respect to KEOF (after removing weighted mean difference)

	PMX(mas)	PMY (mas)
IRIS multibaseline	0.55	1.63
NAVNET	0.44	0.57
CSR SLR	0.44	0.36

5. CONCLUDING REMARKS

High time resolution measurement of Earth rotation is an area of intense activity, involving international and interdisciplinary cooperation. The international campaign, SEARCH'92, is now under way to obtain high time resolution (sub-daily) measurements of Earth orientation by all of the space geodetic techniques and to collect the best available complementary geophysical, oceanographic and atmospheric data. This paper featured the motivation for these measurements and reviewed the progress and planning of SEARCH'92. The earlier campaigns, ERDE and GIG'91, were also discussed; analysis results from ERDE, GIG'91 and SEARCH'92 were highlighted. The initial "real-time" results from SEARCH'92 are indeed encouraging; further analysis will provide new and unique insights into the properties and origin of short period fluctuations in the Earth's orientation and into solid Earth-atmosphere interactions.

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1. Dickey, J. O., Atmospheric Excitation of the Earth's Rotation: Progress and Prospects via Space Geodesy, *American Geophysical Union Monograph, Space Geodesy and Geodynamics*, ed. D. Turcotte, in press (1992).

2. Munk, W. H., and G. J. F. MacDonald, *The Rotation of the Earth*, Cambridge University Press, 1960.

3. Cazenave, A. (ed.), *Earth Rotation: Solved and Unsolved Problems, NATO Advanced Institute Series C: Mathematical and Physical Sciences Vol. 187*, ed. A. Cazenave, D. Reidel, Boston (1986); Dickey, J. O., and T. M. Eubanks, The Application of Space Geodesy to Earth Orientation Studies, Space Geodesy and Geodynamics, eds., A. J. Anderson and A. Cazenave, Academic Press, New York, 221-269 (1986); Hide, R., Towards a Theory of Irregular Variations in the Length of the Day and Core-Mantle Coupling, *Phil. Trans. Roy. Soc.*, A284, 547-554 (1977); Hide, R., Rotation of the Atmospheres of the Earth and Planets, *Phil. Trans. R. Soc. Lond.* A313, 107-121 (1984); Hide, R., Presidential Address:

The Earth's Differential Rotation, *Quart. J. Roy. Astron. Soc.*, 278, 3-14 (1986); Hide, R. Fluctuations in the Earth's Rotation and the Topography of the Core-Mantle Interface, *Phil. Trans. Roy. Soc.*, A328, 351-363 (1989); Hide, R., and J. O. Dickey, Earth's Variable Rotation, *Science*, 253, 629 (1991); Lambeck, K., *The Earth's Variable Rotation*, Cambridge Univ. Press, London and New York (1980); Lambeck, K., *Geophysical Geodesy, The Slow Deformation of the Earth*, Clarendon Press, Oxford (1988); Lambeck, K., and A. Cazenave, *Philos. Trans. R. Soc. London A* 284, 495-506 (1977); Moritz, H., and I. I. Mueller, *Earth Rotation: Theory and Observation*, The Ungar Publishing Co., New York (1987); Wahr, J. M., The Earth's Rotation, *Ann. Rev. Earth Planet Sci.*, 16, 231-249 (1988).

4. Rosen, R. D., D. A. Salstein, T. M. Wood, Discrepancies in the Earth-Atmosphere Angular Momentum Budget, *J. Geophys. Res.*, 95, 265-279 (1990).

5. Herring, T. A., and D. Dong, Current and Future Accuracy of Earth Orientation Measurements, *Proceedings of the AGU Chapman Conference on Geodetic VLBI: Monitoring Global Change*, ed. W. Carter (NOAA Technical Report NOS 137 NGS 49), 306-324 (1991).

6. Dickey, J. O., S. L. Marcus, J. A. Steppe, and R. Hide, The Earth's Angular Momentum Budget on Seasonal Time Scales, *Science*, 255, 321-324 (1992).

7. Ponte, R. M., Barotropic Motions and the Exchange of Angular Momentum Between the Oceans and Solid Earth, *J. Geophys. Res.*, 95, 11, 369-11, 374 (1990).

8. Clark, T. A., J. W. Ryan, and K. D. Baver, ERDE: High Resolution Observations of Earth Orientation Parameters by Very Long Baseline Interferometry, *EOS, Trans. Amer. Geophys. Union*, 71, 1271 (1990).

9. Herring, T. A., D. Dong, and R. W. King, Sub-milliarcsecond Determination of Pole Position using Global Positioning System Data, *Geophys. Res. Lett.*, 18, 1893-1896 (1991).

10. Lindqwister, U. J., A. P. Freedman, and G. Blewitt, Daily Estimates of the Earth's Pole Position with the Global Positioning System, *Geophys. Res. Lett.*, 19, 845-848 (1992).

11. Lichten, S. M., S. L. Marcus, and J. O. Dickey, Sub-Daily Resolution of Earth Rotation Variations with Global Positioning System Measurements, *Geophys. Res. Lett.*, 19, 536-540 (1992).

12. Ray, J., Private communication (1992).

13. Clark, T., International GPS Service Bulletin (1992).

14. Yoder, C. F., M. W. Parke, and J. G. Williams, Tidal Variations of the Earth's Rotation, *J. Geophys. Res.*, 86, B2, 881-891 (1981).

15. Baader, H. -R., P. Brosche, and W. Hovel, Ocean Tides and Periodic Variations of the Earth's Rotation, *J. Geophys.*, 52, 140-142 (1983).

16. Brosche, P., U. Seiler, J. Sündermann, and J. Wünsch, Periodic Changes in Earth's Rotation due to Oceanic Tides, *Astron. Astrophys.*, 220, 318-320, 1989; Brosche, P., J. Wünsch, J. Campbell, and H. Schuh, Oceanic Tide Effects in Universal Time Detected by VLBI, *Astron. Astrophys.*, 245, 676-682 (1991).

17. Dickman, S. R., Dynamic Ocean Tide Effects on Earth's Rotation, submitted to the *Geophys. J. Int.* (1992).

18. Dickey, J. O, S. L. Marcus, and S. M. Lichten, Comparison of Sub-Daily Earth Rotation Variations with Predictions from Oceanic Tidal Model, in *Proceedings of the Sixth International Geodetic Symposium on Satellite Positioning*, ed., P. J. Fell, (Ohio State University, March 17-20, 1992), 259 (1992).

19. Gross, R. S., and U. J. Lindqwister, Atmospheric Excitation of Polar Motion during the GIG'91 Measurement Campaign, *Geophys. Res. Lett.*, 19, 849-852 (1992).

20. Gross, R. S., A Combination of Earth Orientation Data: SPACE91, in *IERS Technical Note: Earth Orientation and Reference Frame Determinations, Atmospheric Excitation Functions, up to 1991* (Annex to the IERS Annual Report for 1991), ed., M. Feissel, in press, Observatoire de Paris, Paris, France; Morabito, D. D., T. M. Eubanks and J. A. Steppe, Kalman Filtering of Earth Orientation Changes, *The Earth's Rotation and Reference Frames for Geodesy and Geodynamics*; Babcock, eds., A. K. and G. A. Wilkens, Kluwer's Academic Publishing, Dordrect, 257-268 (1988).

21. Lambeck, K., Changes in Length of Day and Atmospheric Circulation, *Nature*, 286, 104 (1980).

22. Freedman, A. P. and T. Leung, Private Communications (1992).

23. Salstein, D. A. and D. M. Kann, in Developments at the Sub-Bureau for Atmospheric Angular Momentum of the IERS, *Proceedings of the AGU Chapman Conference on Geodetic VLBI: Monitoring Global Change*, ed. W. Carter, NOAA Technical Report NOS 137 NGS49, Wasington, D. C., 228-237 (1991).